Multi-Fluid Simulations of ICF Implosions

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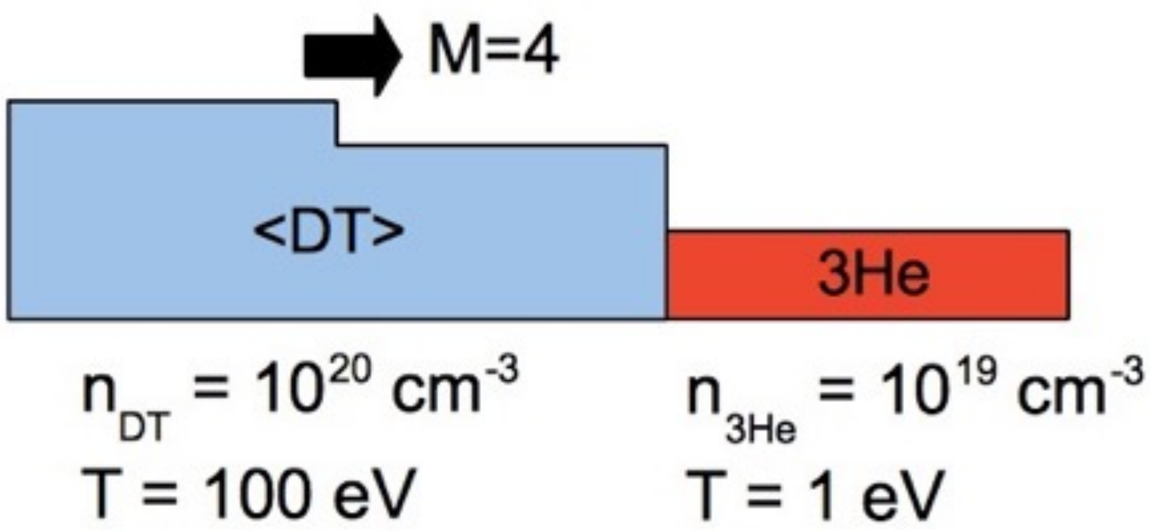
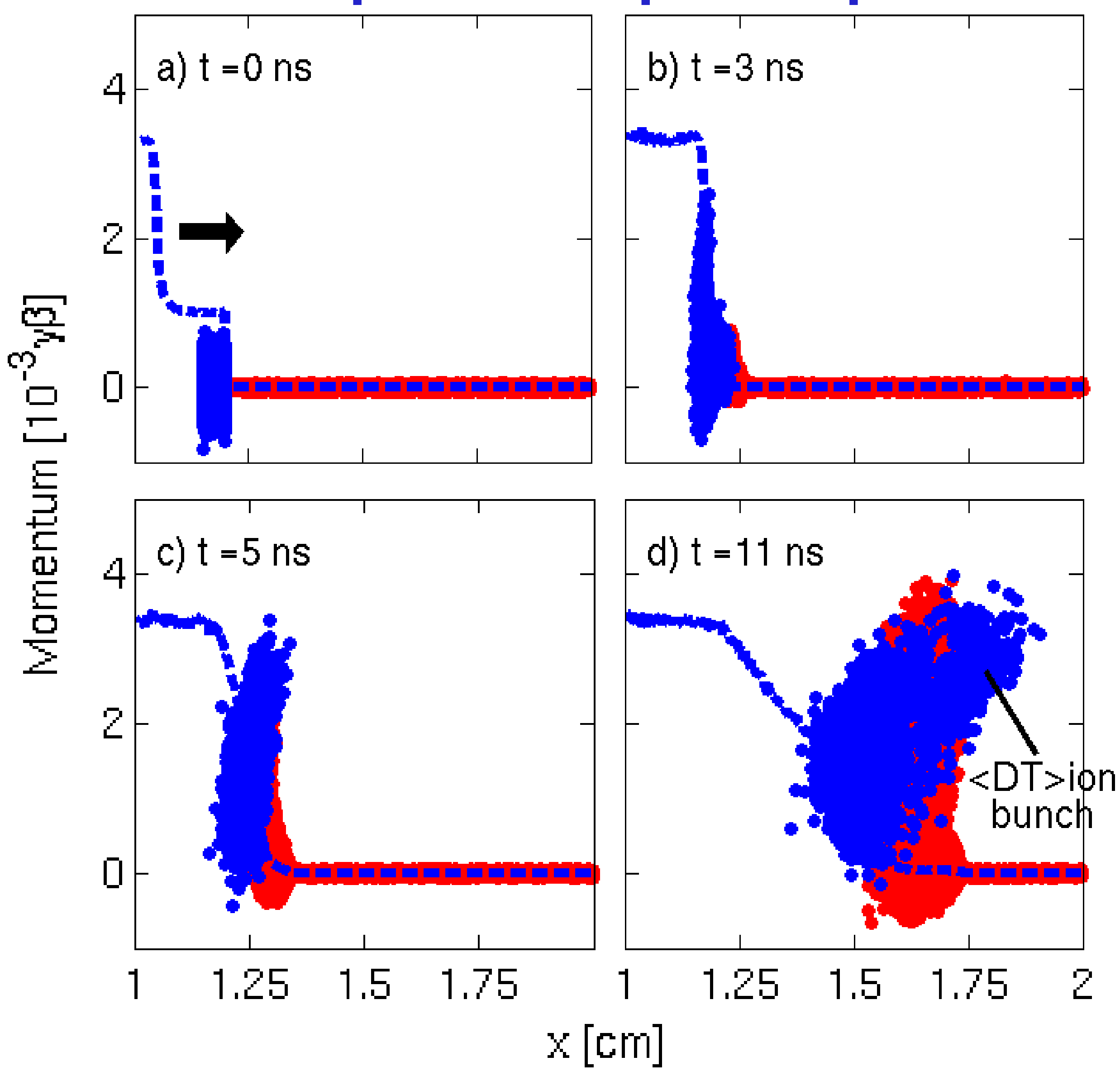
Motivation: LSP simulations with kinetic ions and fluid electrons show significant amounts of material advected with the shock

C. Bellei, P. Amendt, S. Wilks et al., APS2013



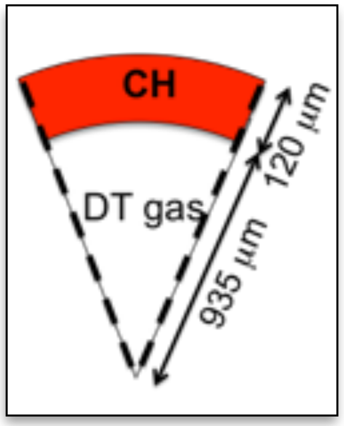
Snapshots of phasespace



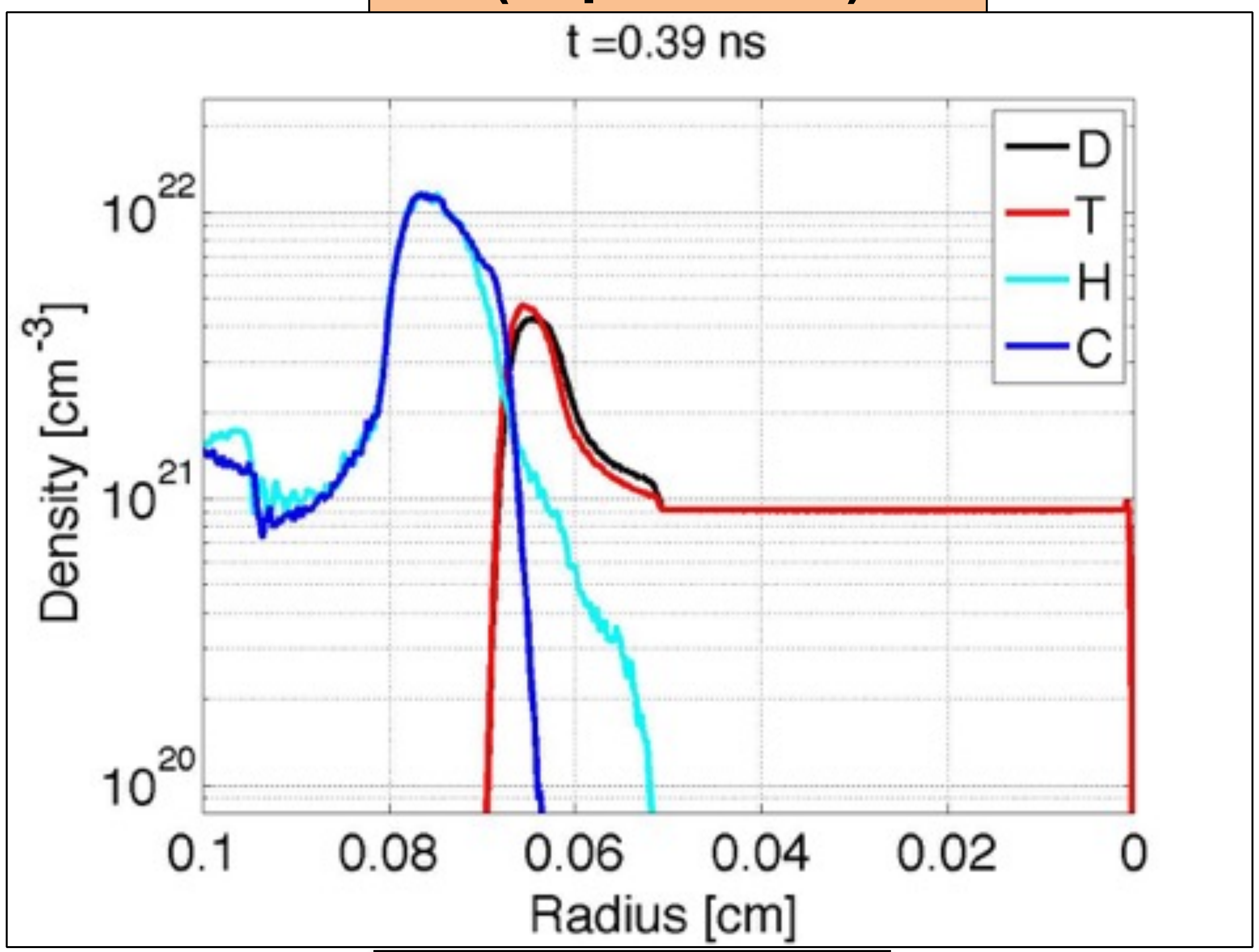
- **Blue** dots: <DT> ions
  Red dots: ^{3}He ions

- Dashed blue lines: <DT> density

Application: NIF indirect drive "exploding pusher"

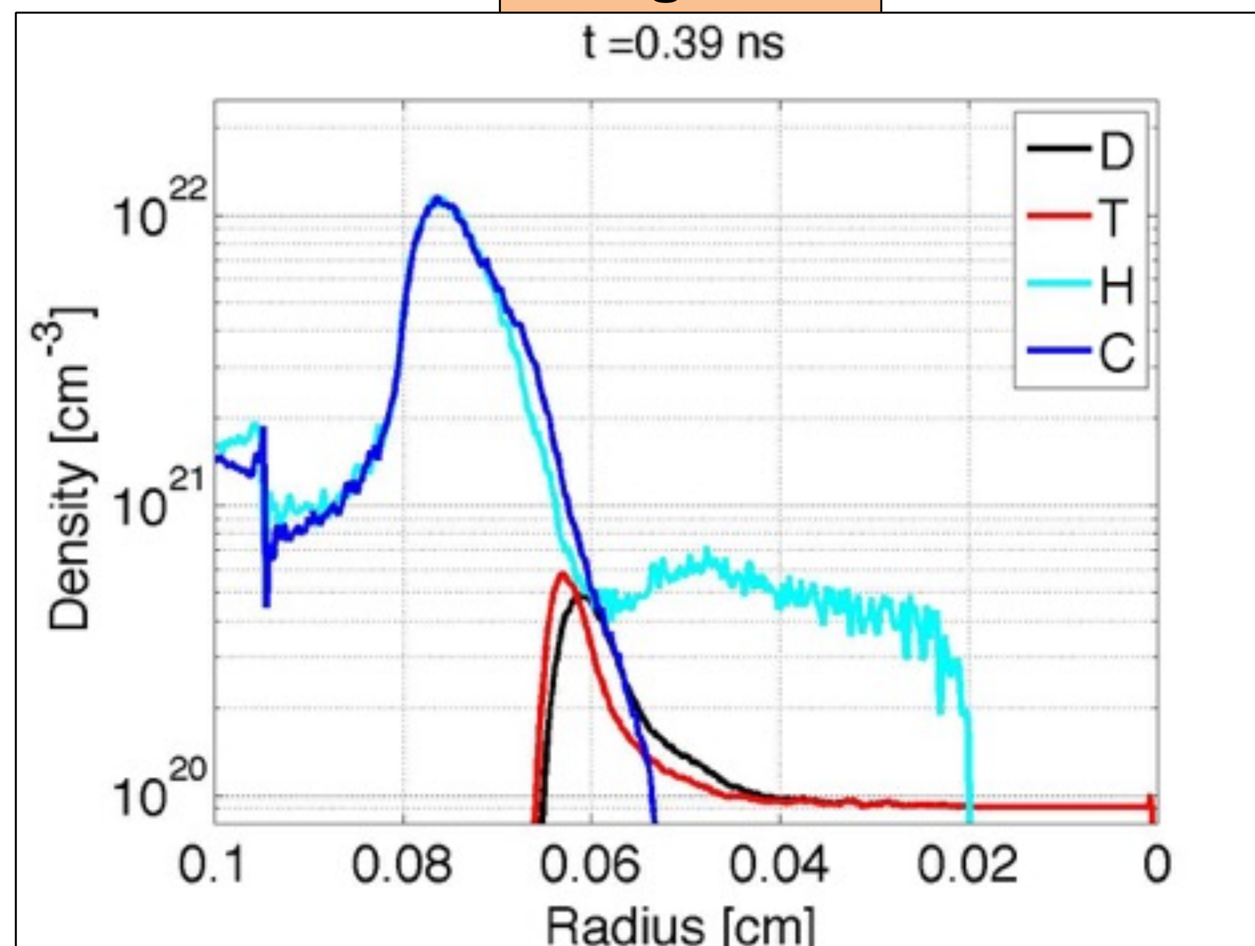


Hydro regime (experiment)



ρ_{gas} = 7.7 mg/cc

Kinetic regime

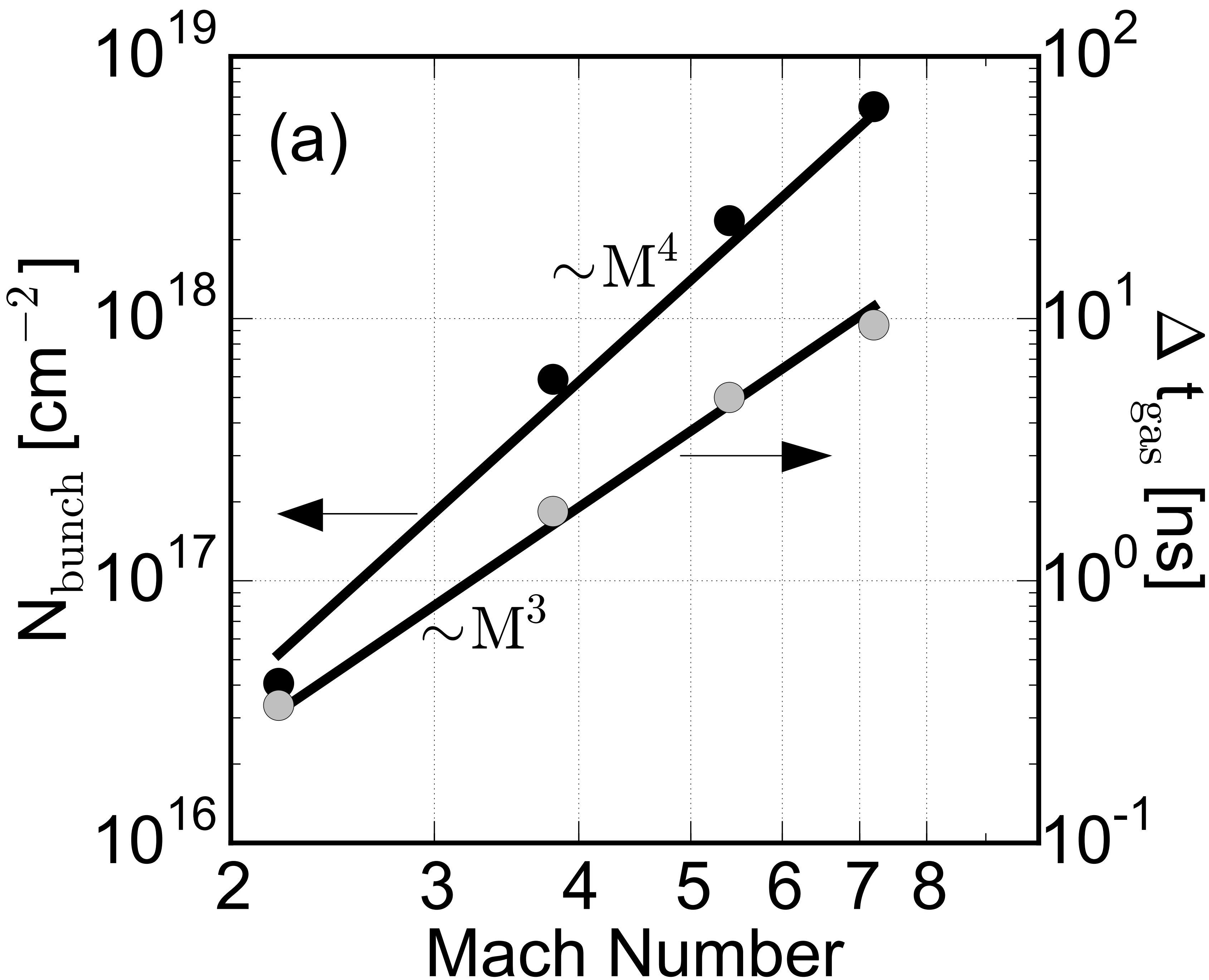


ρ_{gas} = 0.77 mg/cc

Mix from "beaming": non-hydro, non-classical diffusion

Mix scales strongly with Mach number

C. Bellei and P. Amendt, AA2015



Multi-fluid equations are obtained after applying Chapman-Enskog method to Fokker-Planck equation*

- Expand distribution function as

$$f_\alpha = f_\alpha^{(0)} + \mathrm{Kn}_{\alpha\alpha}\, f_\alpha^{(1)} + \ldots \qquad\qquad \mathrm{Kn}_{\alpha\alpha} \ll 1$$

- Coupling between different species is described by a friction term

$$F_{\alpha,F} = \frac{n_\alpha n_\beta T_{\alpha\beta}}{D_{\alpha\beta}}(v_\beta - v_\alpha)$$

- Multi-species simulations give surprisingly good results compared with kinetic calculations**

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* M. S. Benilov, Phys. Plasmas **4**, 521 (1996)

P. J. Rambo and R. J. Procassini, Phys. Plasmas **2, 3130 (1995)

Single-fluid vs. multi-fluid equations

- Ideally we would like to solve the FP equation for all species

$$\frac{\partial f_\alpha}{\partial t} + \mathbf{u}_\alpha \cdot \nabla_x f_\alpha + \mathbf{F}_\alpha \cdot \nabla_u f_\alpha = \left(\frac{\partial f_\alpha}{\partial t}\right)_c$$

- Introduce a Knudsen number $\mathrm{Kn}_{\alpha\beta} = \lambda_{\alpha\beta}/L$

single-fluid $\mathrm{Kn}_{\alpha\beta} << 1 \quad \forall \alpha, \beta$

multi-fluid $\begin{cases} \mathrm{Kn}_{\alpha\alpha} << 1 \\ \mathrm{Kn}_{\alpha\beta} = O(1) \quad \alpha \neq \beta \end{cases}$

Multi-fluid equations for ions (Eulerian)

- Multi-fluid equations (ideal EOS, γ=5/3)

IONS (α=1,2,…,n)

$$\begin{cases} \partial_t \rho_\alpha + \partial_x(\rho_\alpha u_\alpha) = 0 \\ \partial_t(\rho_\alpha u_\alpha) + \partial_x(\rho_\alpha u_\alpha^2 + p_\alpha) = \underbrace{F_{\alpha,E}}_{\text{electric field foce}} + \underbrace{F_{\alpha,F}}_{\text{friction force}} \\ \partial_t(3/2p_\alpha + 1/2\rho_\alpha u_\alpha^2) + \partial_x(5/2p_\alpha u_\alpha + 1/2\rho_\alpha u_\alpha^3) = u_\alpha F_{\alpha,E} + u_\alpha F_{\alpha,F} + \Delta\mathcal{E}_{\alpha,\Delta T} \end{cases}$$

where

$$F_{\alpha,E} = Z_\alpha n_\alpha E$$

$$\Delta\mathcal{E}_{\alpha,\Delta T} = n_1\left[\nu_{12}(T_2 - T_1) + \nu_{1e}(T_e - T_1)\right]$$

$$\sum_\alpha \mathcal{F}_{\alpha,F} = 0 \quad \text{(momentum conservation)}$$

Equations for electrons

- Multi-fluid equations (ideal EOS, γ=5/3)

ELECTRONS

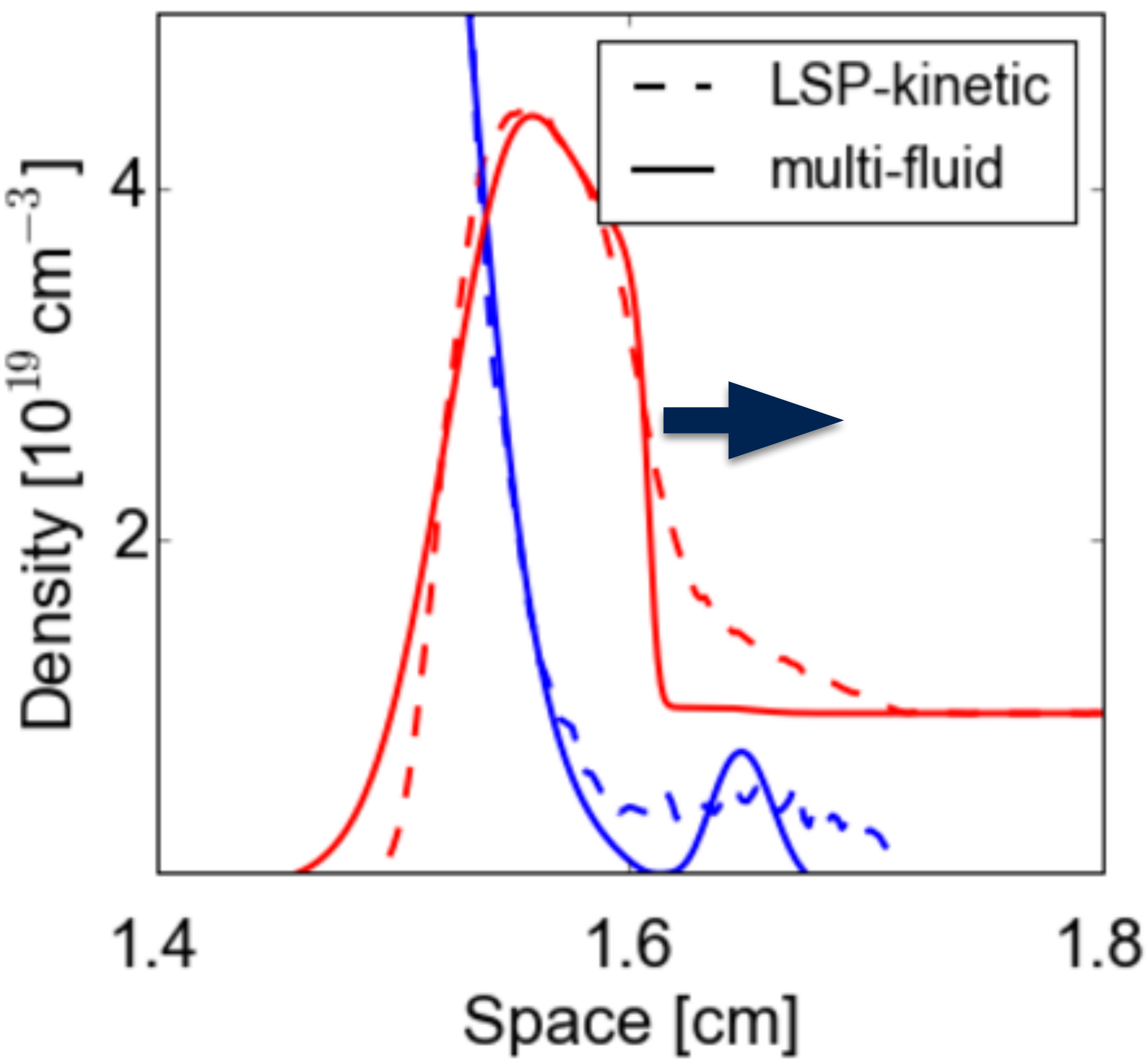
$$
\begin{cases}
n_\mathrm{e} = \sum Z_\alpha n_\alpha \quad \text{(quasi-neutrality)} \\
n_\mathrm{e} u_\mathrm{e} + \sum Z_\alpha n_\alpha u_\alpha = 0 \quad \text{(zero net-current)} \\
\partial_t (3/2 p_\mathrm{e} + 1/2 \rho_\mathrm{e} u_\mathrm{e}^2) + \partial_x (5/2 p_\mathrm{e} u_\mathrm{e} + 1/2 \rho_\mathrm{e} u_\mathrm{e}^3) = u_\mathrm{e} F_{\mathrm{e},E} + \Delta \mathcal{E}_{\mathrm{e},\Delta T} - \partial_x (k_e \partial_x T_e) + Q'
\end{cases}
$$

$$E = -\nabla p_\mathrm{e} / e n_\mathrm{e}$$

where

$$Q' + \sum_\alpha \mathcal{F}_{\alpha,F} u_\alpha = 0 \qquad \text{(for energy conservation)}$$

We observe ion bunch formation also in multi-fluid simulations



What is new from AA 2015:

- Generalized code to any number of ion species
- Spherical geometry
- Included ion viscosity in momentum and energy equations*

*E. L. Vold et al., arXiv 2015

A diffusion model does not predict the formation of an ion bunch and under-predicts mix

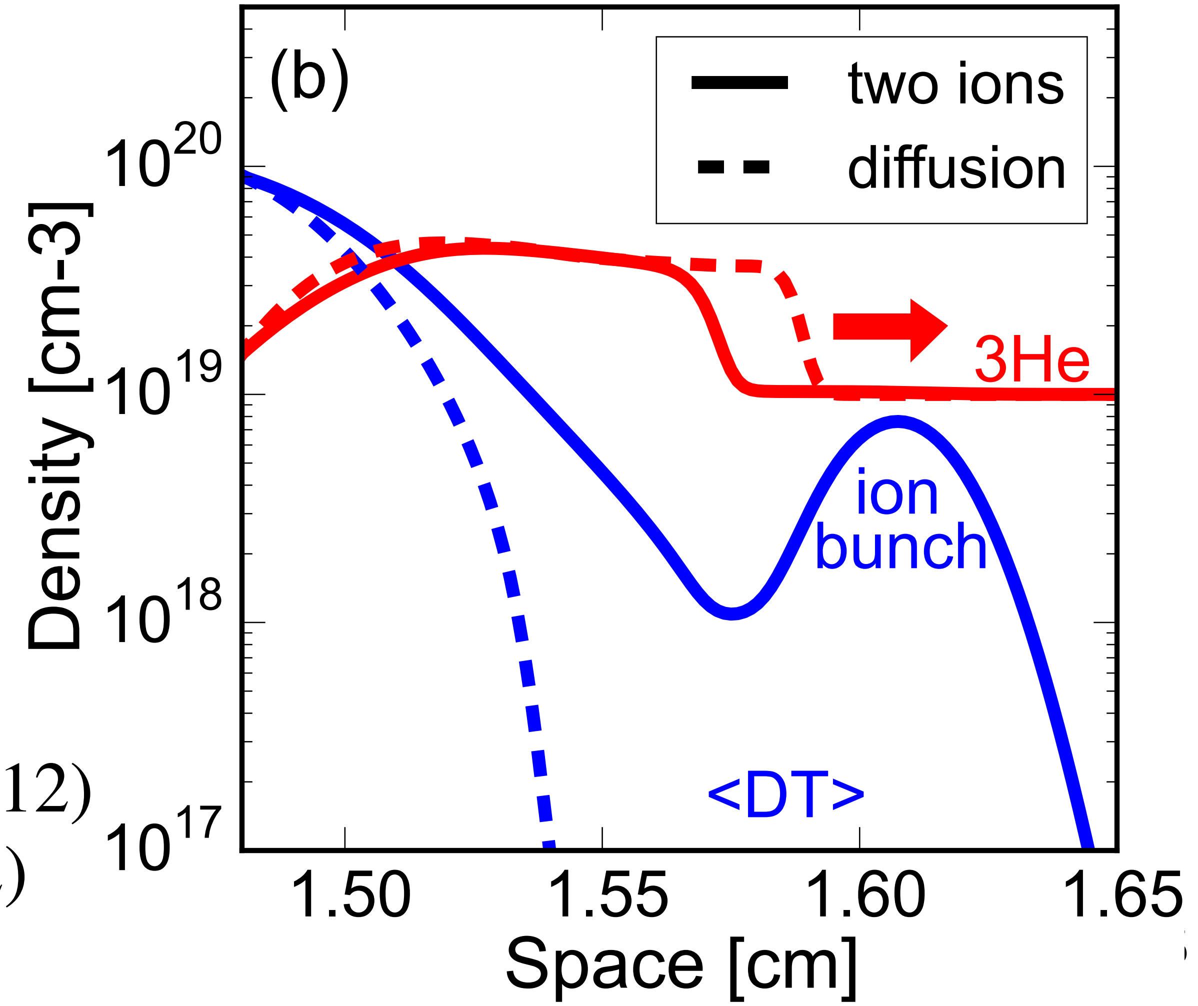
$$\begin{cases} \partial_t \rho + \partial_x(\rho u) = 0 \\ \partial_t(\rho u) + \partial_x(\rho u^2 + p) = F_E \\ \partial_t(3/2p + 1/2\rho u^2) + \partial_x(5/2pu + 1/2\rho u^3) = uF_E + \Delta\mathcal{E}_{\Delta T} + \sum_{i=1,2} h_i J_i \\ \partial_t \rho_1 + \partial_x(\rho_1 u) = -\partial_x J_1 \end{cases}$$

$\boxed{\text{+ electrons}}$

where*,**

$$J_1 = -\rho D \left(\nabla c + k_p \nabla p_i - \frac{k_E}{T} E \right)$$

$\sum_{i=1,2} h_i J_i$ interdiffusion of enthalpy



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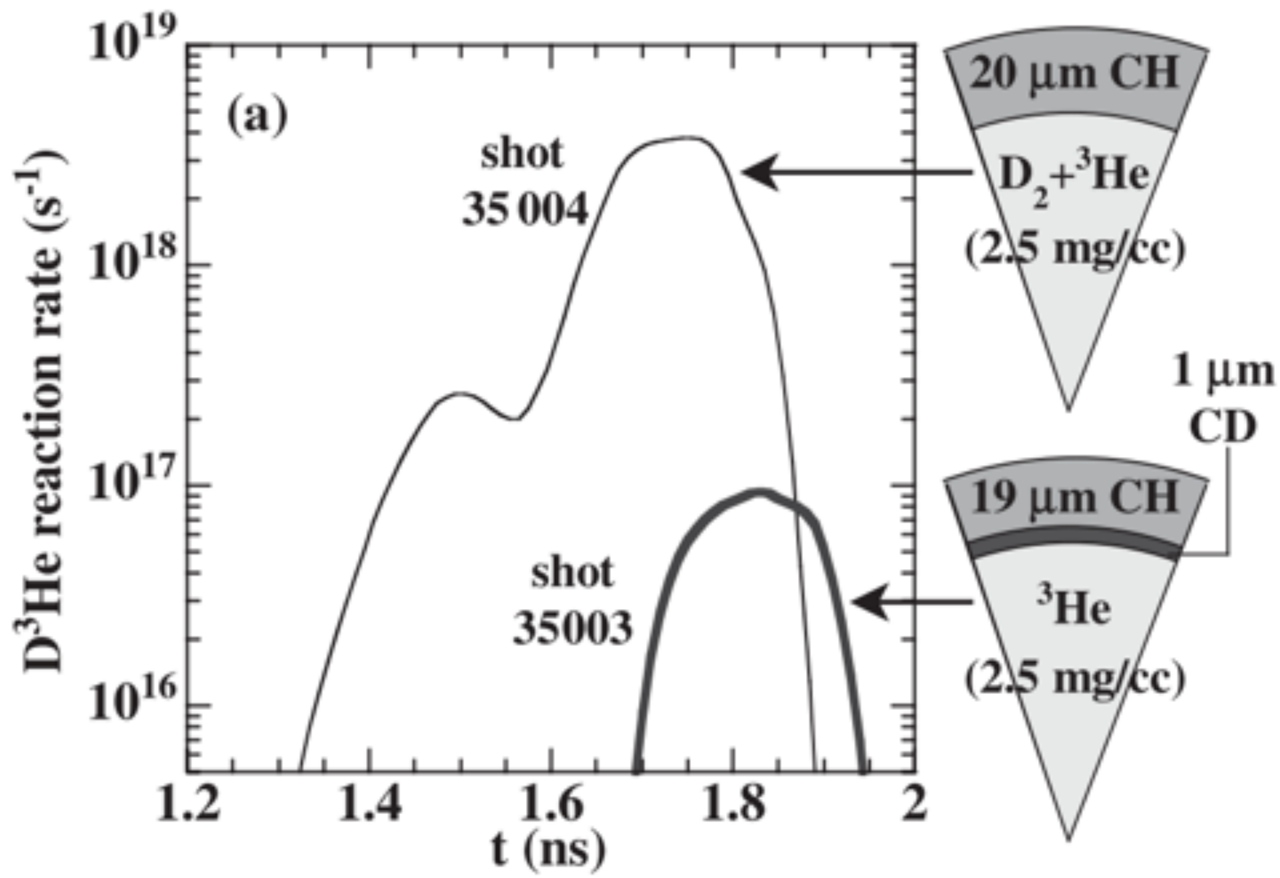
* P. Amendt, et al., Phys. Rev. Lett. **109**, 075002 (2012)
G. Kagan, X. Tang, Phys. Plasmas **19**, 082709 (2012)

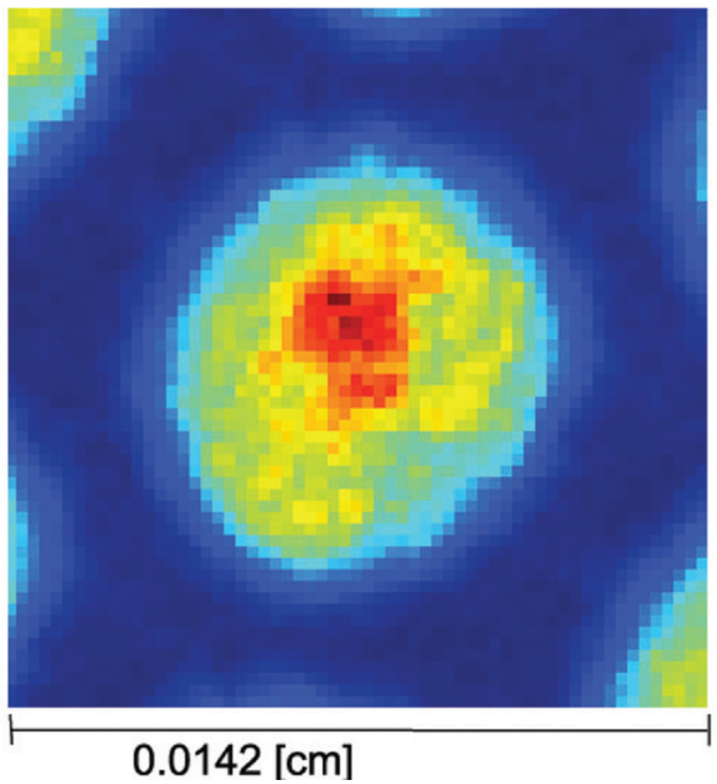
Existence of ion bunch is challenged by/consistent with experimental results

…challenged by…



J. R. Rygg et al.,
PRL **98**, 215002 (2007)

…consistent with…

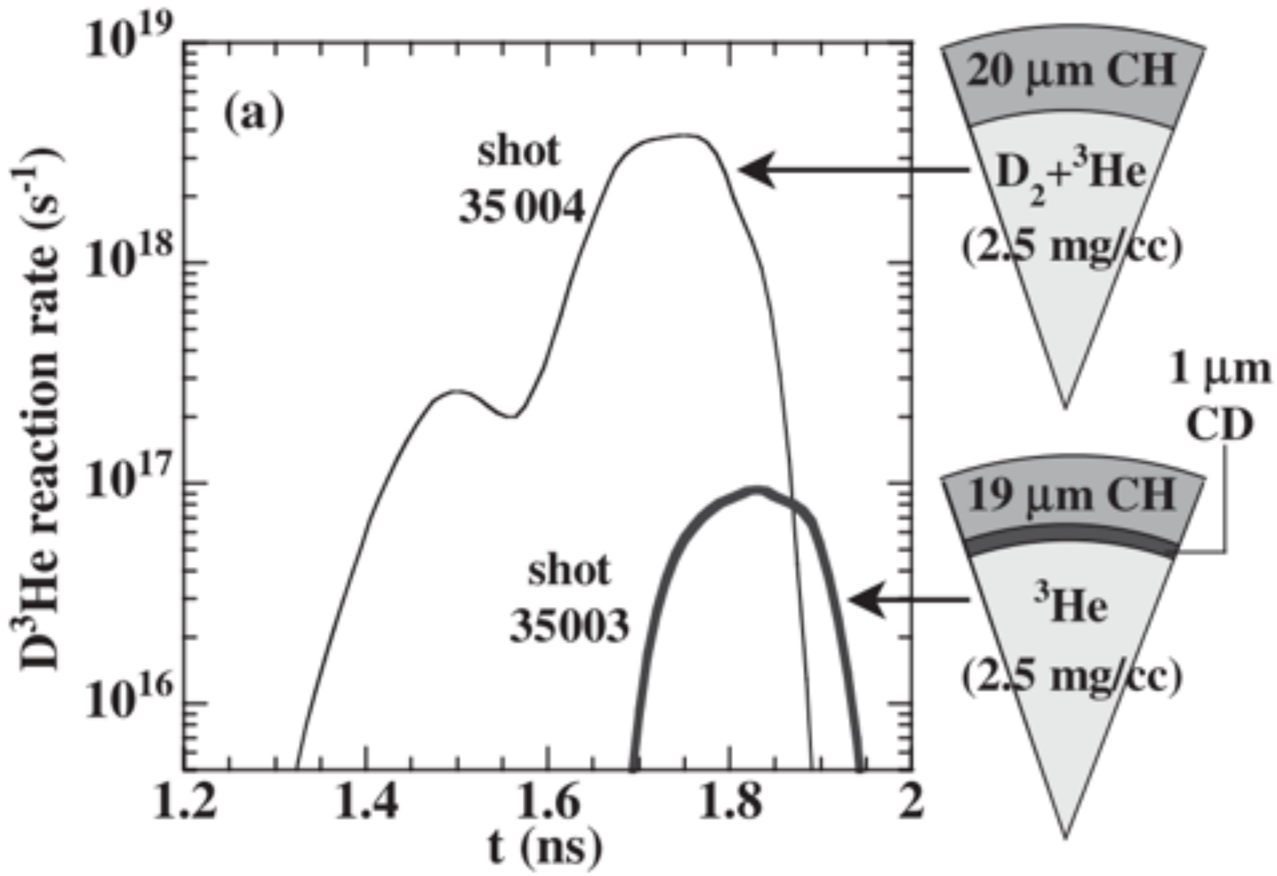


Ti Ly-α at 1.45 ns

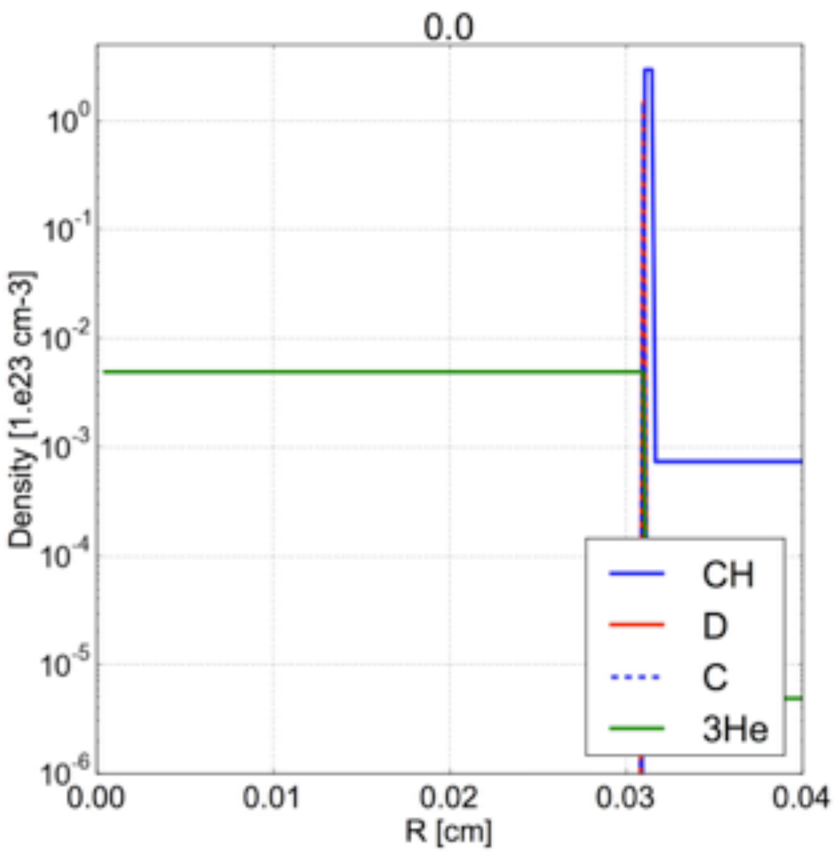
J. A. Baumgaertel et al.,
Phys. Plasmas **21**, 052706 (2014)

Simulations for Rygg et al. show potential formation of D ion bunch

Rygg et al., PRL 2007



multi-fluid



R_0 = 300 μm; ΔR = 5 μm;
T_0 = 5eV; v_{shell} = 225 km/s ; M = $0.4M_0$

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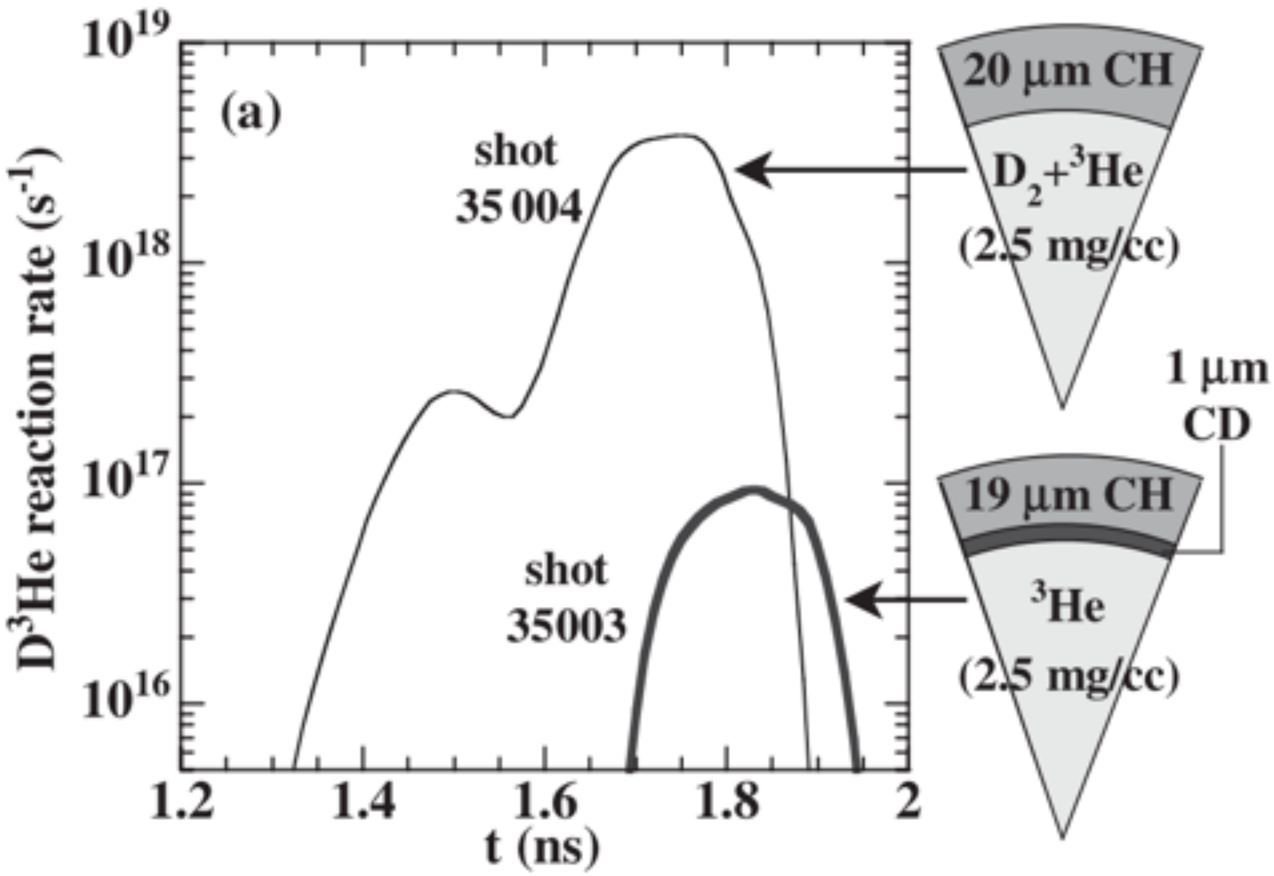

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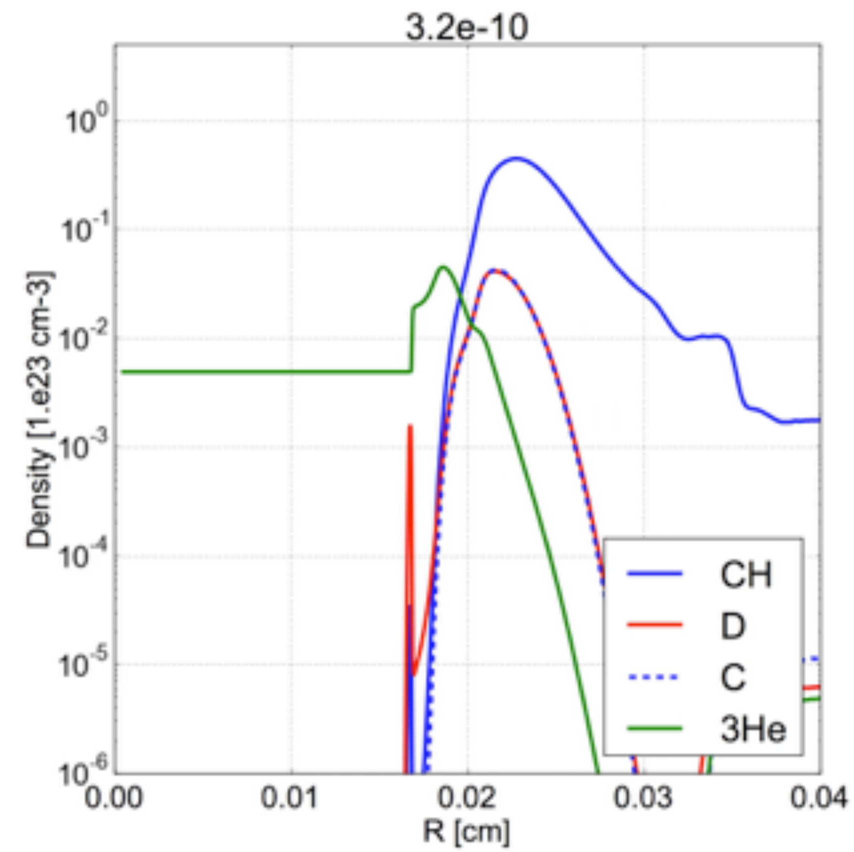

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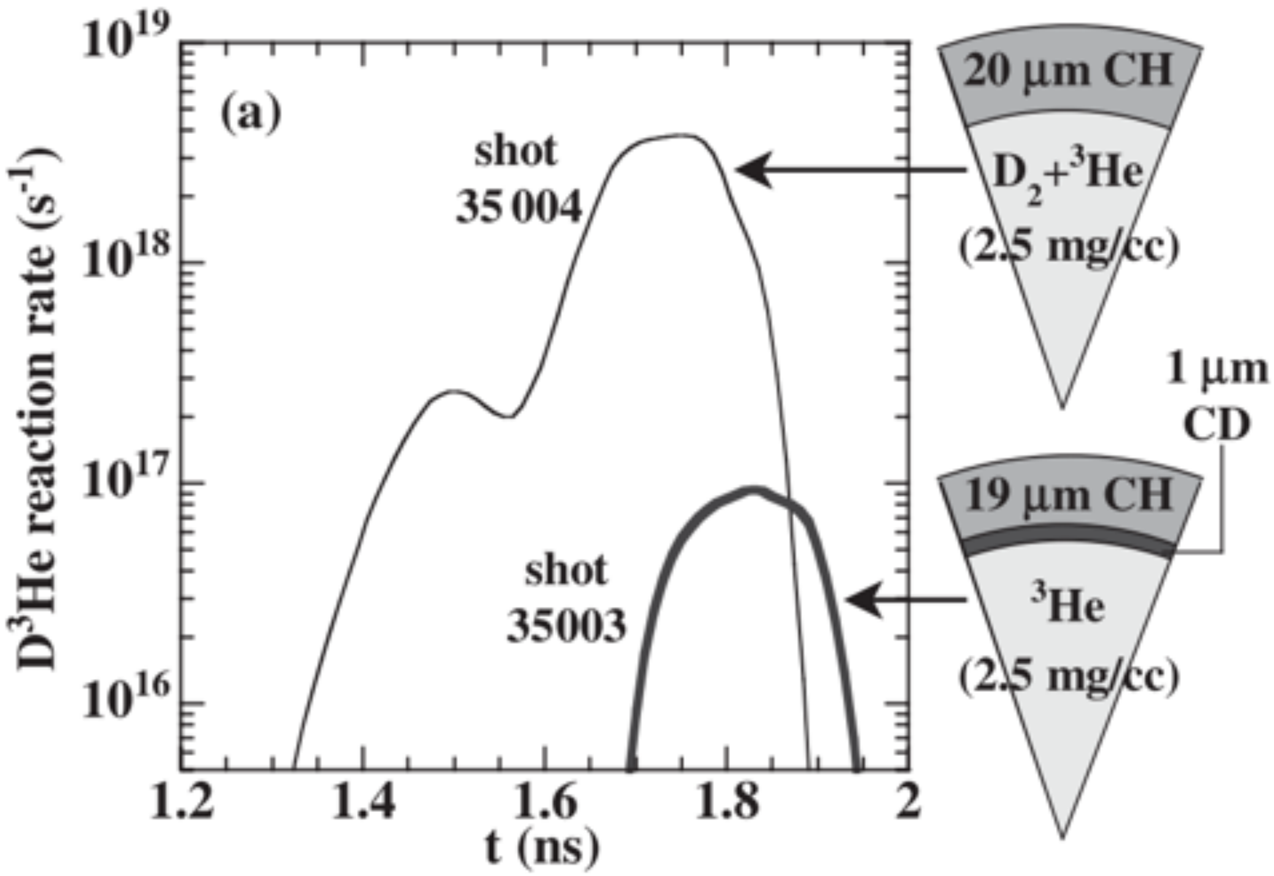

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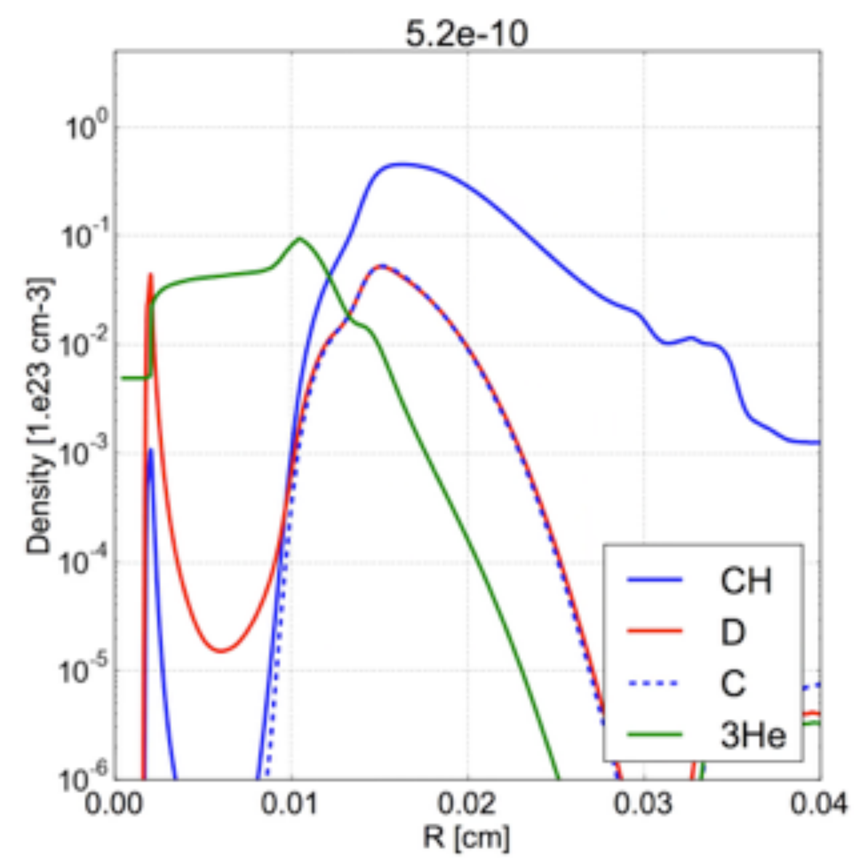

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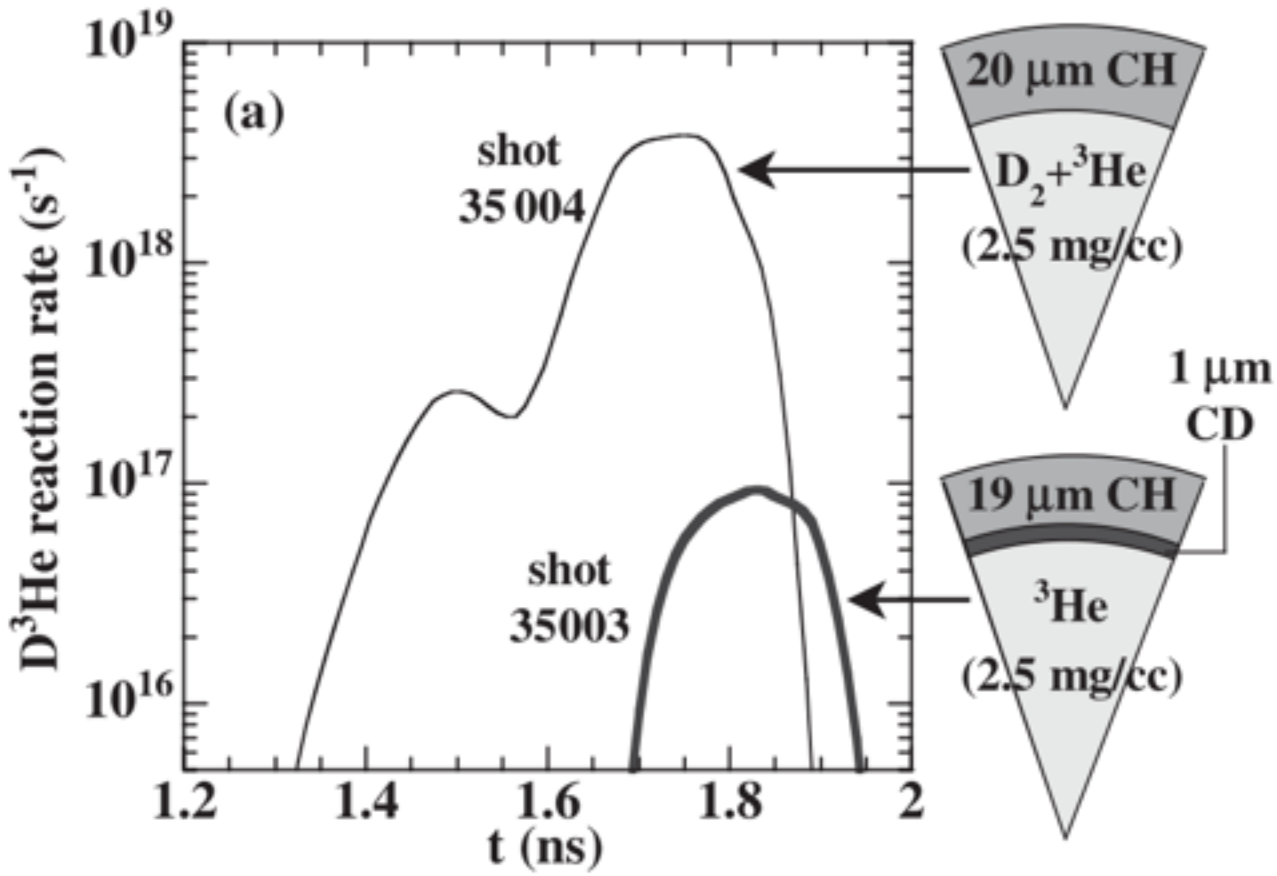
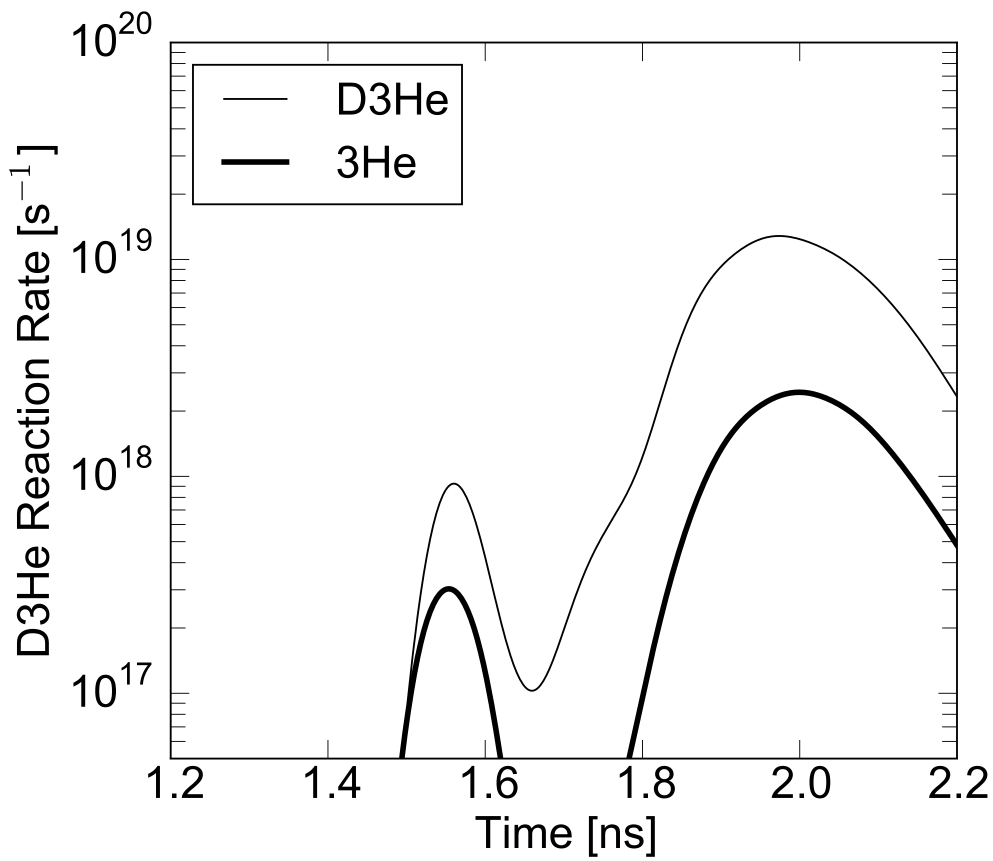
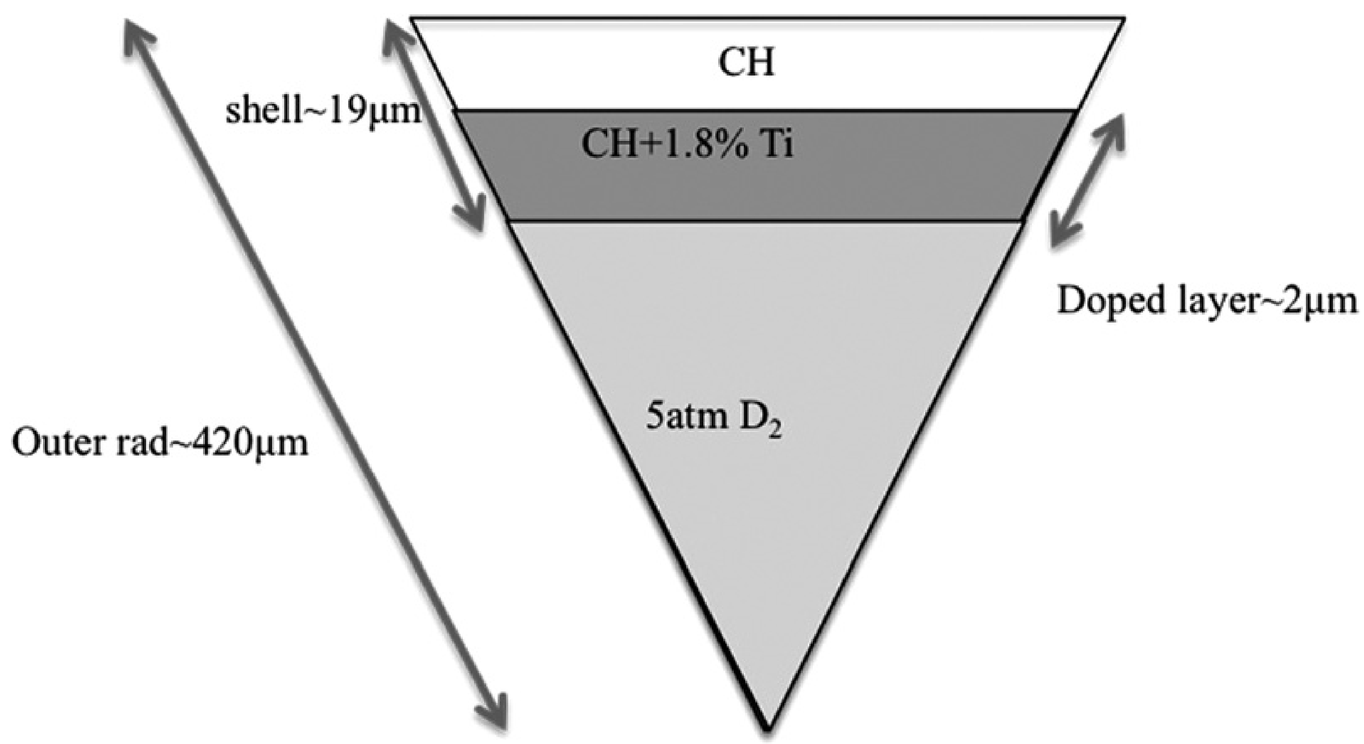


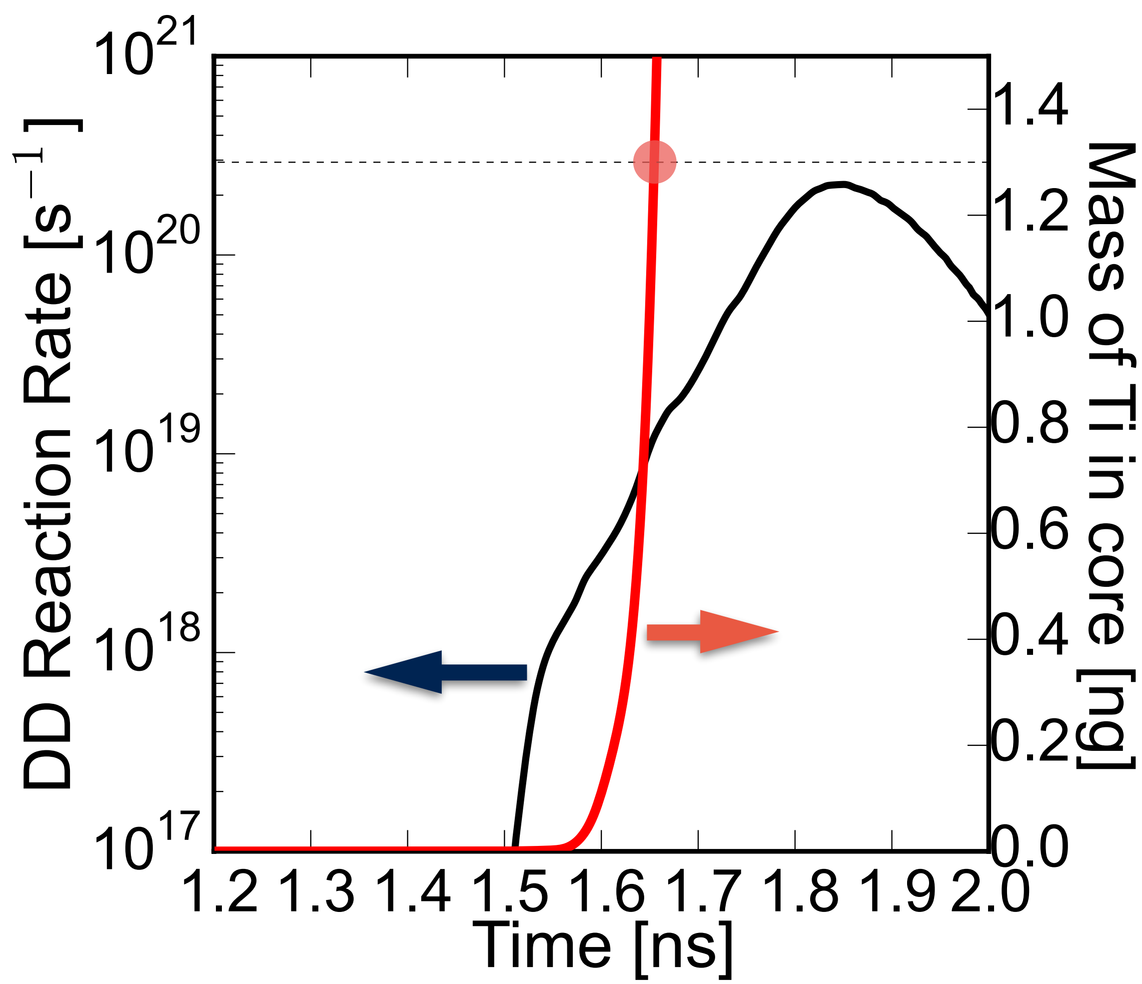
multi-fluid



- reduced D^{3}He fusion yield for ^{3}He case ✔
- compression yield peaks at later time for ^{3}He case ✔
- suppression of shock yield for ^{3}He case ✖

Simulations for Baumgaertel et al. show significant mix of Ti ions in hot spot before bang time, but after shock flash





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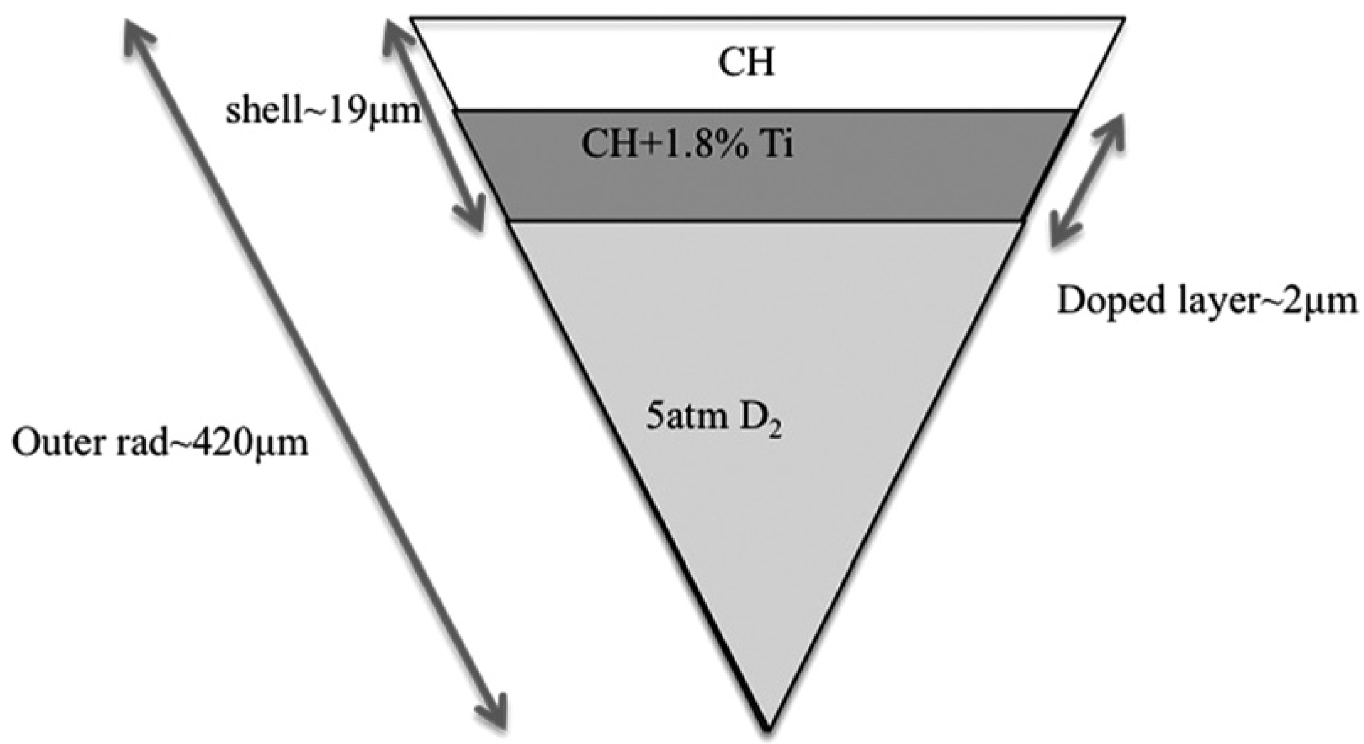

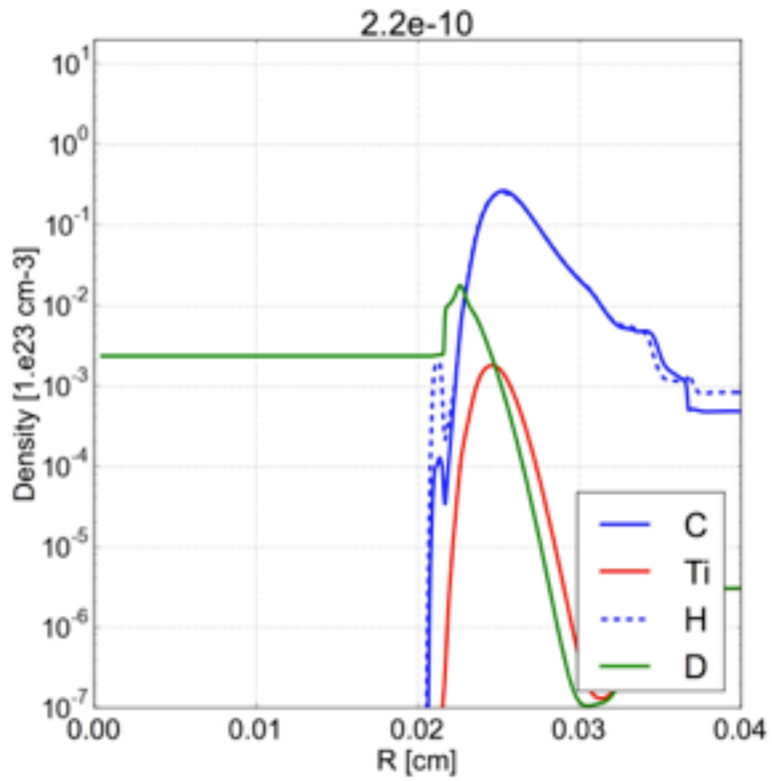

- mass of Ti in hotspot > 1.3 ng ✔
- significant mix at the time of shock flash ✖
- mix region has spherical geometry ✖

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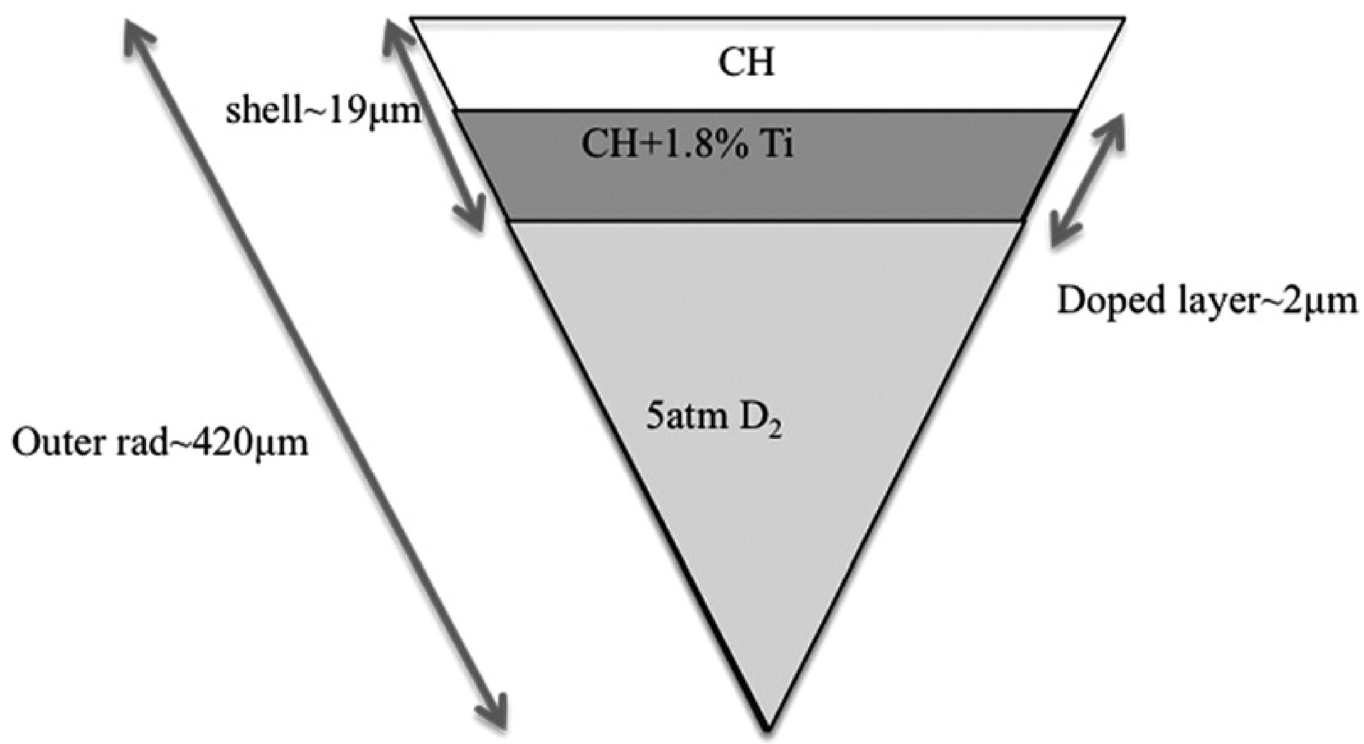

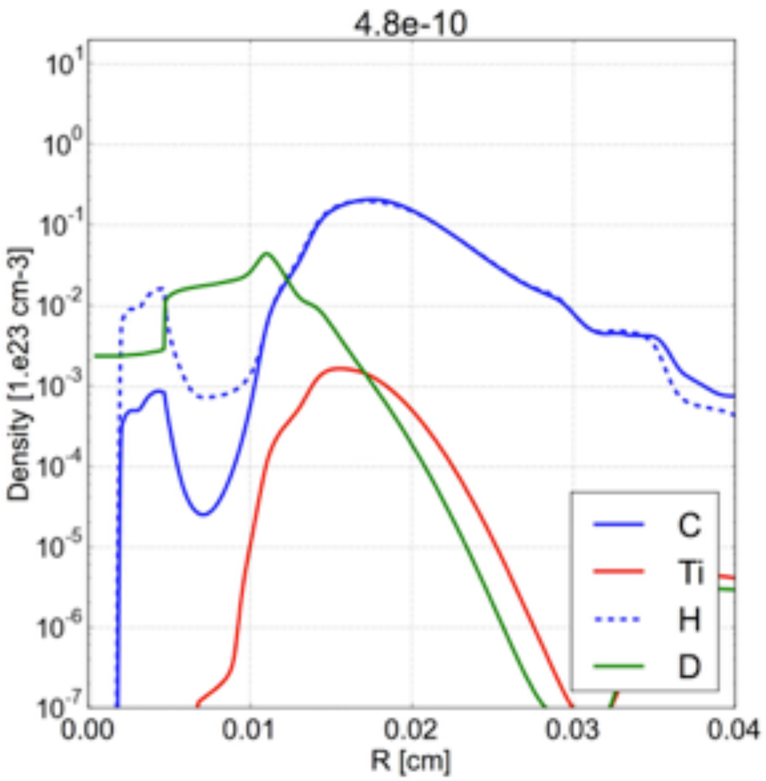

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- significant mix at the time of shock flash ✖
- mix region has spherical geometry ✖

Conclusions and future work

- The mechanism of shock-induced mix is confirmed using different simulation techniques (kinetic, multi-fluid) and codes.
- Difficult to observe this effect for high-Z ions
- There is the potential for an experimental demonstration on OMEGA.

Collaborators

S. Wilks

H. Rinderknecht, A. Zylstra, M. Rosenberg,
H. Sio, C. Li, R. Petrasso

V. Tikhonchuk